



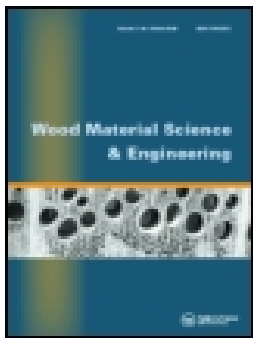
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Evaluation of parameters influencing the load-deformation behaviour of connections with laterally loaded dowel-type fasteners

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ABSTRACT

Connections made with laterally loaded dowel-type fasteners are important details in timber structures. According to Eurocode 5, their load-carrying capacity can be calculated with the so-called European Yield Model (EYM) and simplified rules for the determination of slip-moduli are given. The slip modulus is given as a mean value for the serviceability limit state and a simple reduction of slip modulus in the ultimate limit state is given in addition. Despite these simple regulations, it is well known that connections with dowel-type fasteners show a considerable non-linear load-deformation behaviour with different degrees of ductility. This ductility can enable the load redistribution in complex and statically undetermined structures and allow to achieve higher capacities compared to linear elastic design. In the paper, the deformation behaviour of connections with laterally loaded dowels dowel-type fasteners is studied based on more than 750 test results of bolted connections. The parameters influencing the slip-modulus, ductility ratio, and ultimate deformation are evaluated. It is focused on the effects of these parameters and the resulting variability in deformation behaviour. Recommendations are given on how different levels of ductility and deformation capacity can be achieved in dependency of the spacing of fasteners and other geometrical parameters.

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Fasteners; connections; joints; slip; ductility; slip-modulus; stiffness

Introduction



Laterally loaded dowel-type fasteners, such as steel dowels, are commonly used to create connections in timber structures. When meeting the requirements regarding the development of ductile behaviour (yielding) of both the steel and timber, the so-called European Yield Model (EYM) can be applied to estimate the load-carrying capacity of these connections. The EYM is based on work by Johansen (1949) and Meyer (1957) and is implemented in the design equations in Eurocode 5 EN 1995-1-1:2004 (CEN 2004). The EYM implies that the slender dowel type fasteners show a considerable non-linear load-deformation behaviour. This consideration of this non-linearity in the load-deformation behaviour (in terms of e.g. stiffness, slip-modulus and ductility) is of particular importance in statically indeterminate structures, i.e. where the internal distribution of forces depends on the load-deformation behaviour of the individual elements. Examples are e.g. combined beams with semi-rigid connections, trusses, built-up columns or timber frames. In other situations, also a sufficient deformation capacity is necessary, e.g. for energy dissipation in seismic situations. Hence, not only the load-carrying capacity but also the deformation behaviour has to be accounted in order to assure the desired reliability of a structure. An example of a failure of structures where the non-linear deformation behaviour of

the fasteners in the connection was not considered is the failure of the formwork of the Sandö-bridge in the 1930s (Granholm 1949).

However, the design formulas and recommendations regarding deformation behaviour of connections made with dowel-type fasteners are very basic in the 2004 version of Eurocode 5. The slip modulus given as a mean value is applicable only in the serviceability limit state, when the structure behaves linearly elastic. Even the recommendations regarding reduction of slip modulus for the ultimate limit state are not sufficient for the analysis of more sophisticated structures. Hence, further information on the load-deformation behaviour of connections and the various parameters of influence is needed, such as the effect of multiple fasteners in a connection on the slip modulus, or the effect of spacing between fasteners on the ductility.

The denotations of the geometry of a connection with dowel-type fasteners between 3 timber members are given in Figure 1: the diameter of the fasteners d , the spacing of the fasteners in direction parallel (a_1) and perpendicular to the grain (a_2), the end distance (a_3) and edge distance (a_4); the thickness of the side members (t_s) and middle member (t_m). The density of the timber members is denoted by ρ .

The relative deformation in such a connection depends on the elastic and plastic deformations in the different

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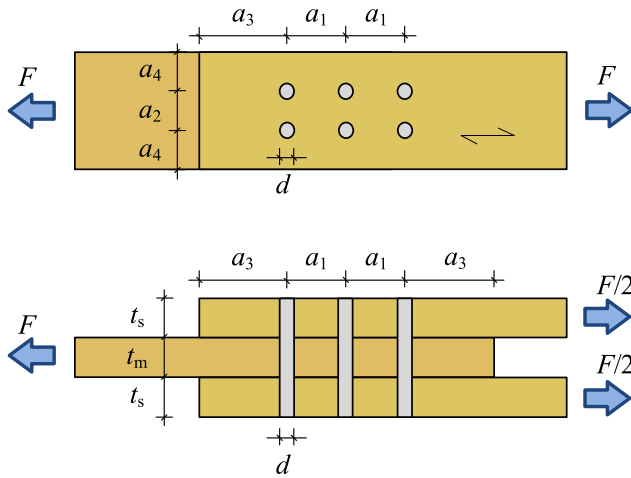


Figure 1. Denotation of geometry of a timber connection with dowels in double shear ($n = 3$ fasteners in a row parallel to grain and $m = 2$ rows of fasteners).

components, i.e. the timber and the fasteners. It can be measured as the relative deformation between the timber members in the vicinity of the fasteners. In tests the measured deformation depends strongly on the position of the measurement and if this measurement is influenced by additional deformations in the members.

In this paper, the deformation behaviour of connections with laterally loaded dowel-type fasteners is studied based on more than 750 test results of bolted connections. The parameters influencing the slip-modulus, ductility ratio, and ultimate deformation are evaluated. It is focused on the effects of these parameters and the resulting variability in deformation behaviour. The content of this paper is based on the results of previous studies by the authors (Jockwer and Jorissen 2018a, 2018b) and is extended by the evaluation of connection ductility and the influences on it.

Background

Slip modulus

Theory

The description of the non-linearity of the load-deformation behaviour of connections is highly complex and subject to a variety of studies (e.g. Kuenzi 1953, Foschi and Bonac 1977, Dolan and Foschi 1991, Heine and Dolan 2001, Lemaître *et al.* 2018). An example of the ductile load-deformation curve of a connection is illustrated in Figure 2. The different parts of the curve can be described as follows: The initial deformation observed at low load levels gives a soft behaviour and a certain initial slip of the connection, that depends amongst others on the tolerances in the assembly of the connection. According to Dubas (1981), the initial slip is commonly smaller for connections tested in laboratory due to the higher precision compared to connections produced in practice.

When the components of the connection are in full contact, the load deformation behaviour becomes approximately linear. This range is typically between 10% and 40% of the maximum load and below the yield point. At higher

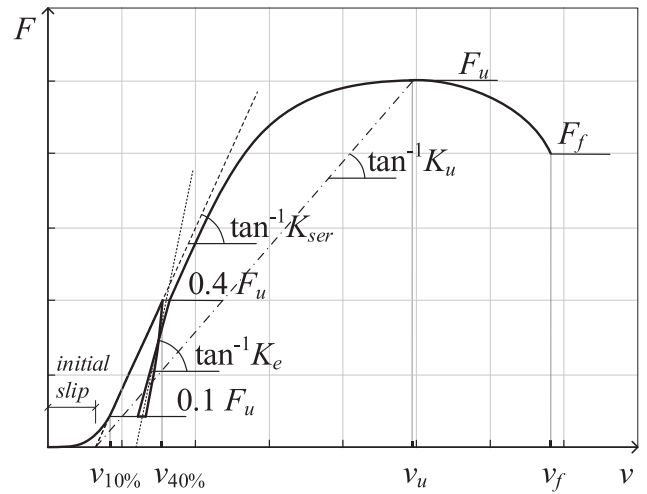


Figure 2. Definitions of different slip-moduli for the non-linear load-deformation curve of a connection.

load levels the load-deformation behaviour becomes non-linear and considerable softer if sufficient ductility is available, until reaching the maximum or ultimate load F_{\max} or F_u . When the deformation is further increased, a decrease of the load can be observed in deformation-controlled tests. Failure is often defined as the point where the load drops below a certain threshold, e.g. 80% of F_u .

From the load-deformation curve, the corresponding slip moduli can be derived as the load divided by the corresponding deformation. A distinguish is made between the tangential slip modulus, calculated as the derivation of the load-deformation curve at a single point, and the secant slip modulus, calculated from the difference of load and deformation between two points along the curve. The slip modulus at serviceability limit state K_{ser} can be considered as approximately tangent to the linear load deformation relationship between 10% and 40% of F_u whereas the slip modulus in the ultimate limit state K_u is defined as the secant between zero and ultimate load as illustrated in Figure 2. In the test standard EN 26981 (CEN 1991) for the determination of the deformation characteristics of connections with mechanical fasteners, the slip modulus K_{ser} for the serviceability limit state is denoted as K_s and can be derived from the estimated maximum load F_{est} and the corresponding deformations v_{01} and v_{04} at 10% and 40% of F_{est} respectively, as follows (Formula (1)):

$$K_s = \frac{0.4 \cdot F_{est}}{\frac{3}{2} \cdot (v_{04} - v_{01})} \quad (1)$$

When performing the connections tests according to EN 26981 with an un- and re-loading cycle between 40% and 10% of F_{est} , also an elastic slip modulus K_e can be determined for this load-cycle according to Formula (2), using the deformations v_{14} and v_{11} at 40% and 10% of F_{est} of the un-loading cycle and v_{21} and v_{24} at 10% and 40% of

F_{est} of the re-loading cycle.

$$K_e = \frac{0.4 \cdot F_{est}}{\frac{2}{3} \cdot (v_{14} + v_{24} - v_{11} - v_{21})} \quad (2)$$

Lemaître *et al.* (2018) developed beam-on-nonlinear-elastic foundation models considering the elastoplastic behaviour of the fastener and its nonlinear elastic embedment in the wood. The advanced modelling of the connection allows to consider different boundary conditions such as fastener slenderness and diameter, connection configuration with different arrangement or thickness of steel plates, or the inclusion of cross-layered materials. However, the modelling also poses a challenge to the definition of the material properties and in particular the embedding properties of the wood-based material. Studies on the determination and definition of embedment properties in dependency of load to grain angle and for different materials are given in Schweigler *et al.* (2016, 2018, 2019).

Specifications in standards

EC5

Eurocode 5 refers to EN 26981 for the determination of the slip modulus K_{ser} in the serviceability limit state and gives formulas for different types of fasteners. For predrilled fasteners, such as dowels, bolts, screws or nails, Eurocode 5 proposes $K_{ser} = \rho_m^{1.5} \cdot d/23$ and for nails without predrilling $K_{ser} = \rho_m^{1.5} \cdot d^{0.8}/30$. No distinction is made between fasteners loaded parallel or perpendicular to the grain. Furthermore, the failure mode of the fastener is not included.

The derivation of these equations are explained in Ehlbeck and Larsen (1993) and are based on the ratio of the load and deformation at 40% of the characteristic load-carrying capacity according to the EYM, which is considered to correspond to the serviceability limit state. The formula for the load is derived by inserting the equations for embedment strength and yield moment (assuming) into the equations of the EYM (neglecting all partial safety factors) for a nail in single shear in the failure mode with 2 plastic hinges per shear plane. The deformation at 40% of the characteristic load-carrying capacity is based on studies by Ehlbeck and Werner (1988a, 1988b) and is specified as follows (Formula (3)):

$$v_{40\%} \approx \frac{40 \cdot d^{0.8}}{\rho_k} \quad (3)$$

The resulting equation for the slip modulus of a connection with predrilled nails of diameters $2 \text{ mm} \leq d \leq 8 \text{ mm}$ is dependent on the diameter and characteristic value of the density of the timber members:

$$K_{ser} = \frac{0.4 \cdot F_{v,Rk}}{v_{40\%}} = \frac{0.55}{100} \sqrt{100 - d} \rho_k^{1.5} d \approx \frac{\rho_k^{1.5} \cdot d}{20} \quad (4)$$

This relation was incorporated in the former German standard DIN 1052 (DIN 2008). For the implementation in Eurocode 5, it was transformed to mean densities.

Lemaître *et al.* (2018) compared the Eurocode 5 approach with their advanced model. It was observed that Eurocode 5 approach underestimates the impact of dowel diameter. The model shows an impact of slenderness of the fastener on the slip-modulus with lower values for a slenderness indicating failure modes without plastic hinges in the fastener.

Swiss standard SIA 265

In the Swiss standard for the design of timber structures SIA 265 the slip modulus K_{ser} in the serviceability limit state is defined as the ratio between load F_y and deformation v_y at the yield point, Formula (5).

$$K_{ser} = \frac{F_y}{v_y} \quad (5)$$

Formulas for the determination of K_{ser} of connections with different fasteners are given for corresponding Service class 1 and for short-term loading, where $K_{ser} = 60 \cdot d^{1.7}$ for nails without predrilling and $K_{ser} = 3 \cdot \rho_k^{0.5} \cdot d^{1.7}$ for dowels, bolts and predrilled nails, all loaded parallel to the grain. In connections with fasteners loaded perpendicular to the grain, the respective values are reduced by 50%.

The derivation of the equations for the slip modulus in SIA 265 is described in Dubas (1981) and are based on tests by Egner (1955) and Möhler and Ehlbeck (1973). The slip modulus K is represented by Equation (6) as a constant and the diameter d with an exponent 1.7. When performing the fitting with the data used by Dubas a constant of 46.9 and an exponent 1.87 for the diameter can be found.

$$K = \text{constant} \cdot d^{\text{exponent}} \quad (6)$$

Fontana (1984) states that these slip moduli values are based on load level of approximately 1.5–2 times the serviceability level. On serviceability level the slip modulus may be up to twice the specified values; Fontana refers in this case to Scheer (1980). According to Dubas (1981) the relatively low slip modulus values were chosen in the standard due to the higher creep in the connection compared to the other timber members (equal creep factors are used both for connections and timber members).

Slip modulus at ultimate limit state

Due to the highly non-linear load-deformation behaviour of a connection, the slip modulus is not constant for the different load levels. In general, a decrease of slip modulus can be observed with increasing deformation. Granholm (1949) determined the tangential and secant slip modulus determined along the entire load-deformation curve of a nailed connection. The curves were calculated based on results from 70 tests on nails $d = 5.6 \text{ mm}$ and length 150 mm. In the case of a collapse of a bridge formwork evaluated by Granholm (1949) the slip modulus at failure due to instability of the system was only approximately 20–25% of the initial values. (Dubas 1981) stated it is not sufficient to only state the slip moduli at the ultimate limit state in a standard,

since that would result in too conservative values for the serviceability limit state.

The experimental determination of K_u is not specified in EN 26891 (CEN 1991). Eurocode 5 specifies the “instantaneous slip modulus for ultimate limit states” as follows but does not give a more specific explanations on how to interpret this value.

$$K_u = \frac{2}{3} K_{ser} \quad (7)$$

Hence, it is not entirely clear if K_u should be considered as the secant slip modulus between 0% load and the maximum load F_u or the load at failure F_f when the load drops below $0,8F_u$. According to Eurocode 5, K_u is calculated from K_{ser} , which is specified as a mean value and no partial factors are considered. According to the German national annex (DIN 2013) to Eurocode 5 the slip modulus for the verification in the ultimate limit state should be calculated considering a partial factor, i.e. $K_u = \frac{2}{3} \frac{K_{ser}}{\gamma_M}$. The use of the general partial

factor, which was calibrated for the reference situation of bending strength verification, does not properly take into account the impact of the variability of stiffness on the reliability of the structure. In addition, this formulation of K_u does not account for brittleness or ductility of the connection when reaching ultimate load. This might be unsafe in certain situations. An example is the case of combined members in partial composite action, where the distribution of forces in the members depends on the relative stiffness of the members and connections connecting them. Considering too high connection stiffness will overestimate the composite action. On the other hand, an underestimation of connection stiffness can lead to an underestimation of the force acting in these connections.

The derivation of Equation (7) can be found in Ehlbeck (1979) and is based on the formula for the load-deformation of nailed connections in different Australian softwood and hardwood species determined by Mack (1966). The formula specifies the load at the given deformation v of the connection in relation to the load at 2.5 mm deformation as follows:

$$\frac{F}{F_{2.5\text{ mm}}} = \left(0.32 \frac{v}{2.5\text{ mm}} + 0.68\right) \left(1 - e^{-7.5 \frac{v}{2.5\text{ mm}}}\right)^{0.7} \quad (8)$$

Ehlbeck calculated the secant slip modulus from zero to the two levels at 0.5 and 1.0 mm deformation, respectively, and derived the relation $K_{1\text{ mm}} = \frac{2}{3} K_{0.5\text{ mm}}$. The choice of these deformation limits made by Ehlbeck (1979) is somehow unclear. In the German standard DIN 1052 from 1988 a deformation at permissible load level of $0.1d \sim 0.2d$ is given for nails with or without predrilling in singles shear or $0.1d$ in double shear, which could be related to these limits.

Ductility

Theory and definitions of ductility

A variety of definitions of ductility can be found in literature and standards. A concise summary was performed by

Muñoz *et al.* (2008). A distinguish is made between relative and absolute definitions that can be based on the deformation or energy. The different ductility definitions presented in Jorissen and Fragiaco (2011) and Malo *et al.* (2011) are shown in the following equations:

Relative, deformation-based definitions:

$$D_u = \frac{v_u}{v_y} \quad (9)$$

$$D_f = \frac{v_f}{v_y} \quad (10)$$

$$D_{f/u} = \frac{v_f}{v_u} \quad (11)$$

$$C_u = \frac{v_u - v_y}{v_u} \quad (12)$$

$$C_f = \frac{v_f - v_y}{v_f} \quad (13)$$

Absolute, deformation-based definitions

$$D_{uy} = v_u - v_y \quad (14)$$

$$D_{fy} = v_f - v_y \quad (15)$$

$$D_{fu} = v_f - v_u \quad (16)$$

Energy based definitions

$$D = \int_0^{v_u} F(v) dv \quad (17)$$

$$D = \frac{\int_0^{v_u} F(v) dv}{\frac{F_u^2}{2 K_{ser}}} \quad (18)$$

This list is not exclusive or complete and further definitions can be found in literature, e.g. (Flatscher 2017). The definition of ductility in Equation (10) is used in Standard SIA 265 (SIA 2012).

Though the relative definitions in Equations (9)–(13) are more frequently used in practice, Jorissen and Fragiaco (2011) conclude that absolute definitions better represent the ductility concept. This conclusion can be supported by the fact that in most cases it is aimed at stiff connections, i.e. achieving high slip moduli in the serviceability limit state up to the yield point. This requires in fact a certain minimum absolute ductility necessary in order to overcome tolerances in the connections when reaching the ultimate limit state and failure capacities.

The deformation-based definitions, Equations (9)–(16), are used within this paper for the evaluation of test results and differences between the relative and absolute definition are discussed.

For the deformation-based definitions of ductility it is necessary to define and identify the deformation v_y at the proportionality limit (yield point), that separates the elastic behaviour from the plastic behaviour. Challenges with regard to the identification of v_y for non-ideal (linear elastically plastic) load-deformation curves are discussed e.g. in Muñoz *et al.* (2008), Malo *et al.* (2011), and Brühl (2020) determined that the value of the yield displacement may vary up to 80% depending on which of the following six methods

that has been used: (Karacabeyli and Ceccotti 1996) describe the yield point as the displacement at 50% of the maximum load, while EN 12512 (CEN 2001) and Swiss standard SIA 265 (SIA 2012), illustrated by Figure 3(a), define the yield point as the intersection point of the slip modulus K_{ser} and a tangent of one-sixth of that value. The approach of Yasumura and Kawai (1998), which is implemented in the Japanese design regulations (HOWTEC 2017), is slightly different from that of EN 12512 and SIA 265: the stiffness of the second secant is defined between 40% and 90% of the ultimate load and the yield point is horizontally projected on the actual load-deformation curve, see Figure 3(b). The Commonwealth Scientific and Industrial Research Organization (CSIRO) identifies the point of yielding at a displacement of 1.25 times the displacement at 40% of the ultimate load. The American National Standards Institute assumes the yielding point as point on graph corresponding to the 5% offset by the fastener diameter of the initial stiffness, measured from zero to 40% of the ultimate load. The method based on the equivalent energy elastic-plastic curve (EEEP) (Foliente 1996) is illustrated in Figure 3(c). This method defines a linear elastic-plastic graph with an initial slip modulus from zero to 40% of the ultimate load that has the same underlying area as the actual load-deformation curve. When applying a relative ductility definition, hence, only one well-defined criterion for the evaluation of the yield displacement v_y should be chosen to avoid inconsistencies due to such large differences.

Muñoz *et al.* (2008) state that the methods by Karacabeyli and Ceccotti (1996) and CSIRO may not predict well the yield point if the elastic region goes beyond a load of 50% of the ultimate load, or if the yield point corresponds to a load higher than 50% of the ultimate load. In fact, in the latter case, the measured yield point will be located in the onset of the plastic deformation, as observed in connections showing residual strength. The methods according to EN 12512 and SIA 265 may instead overestimate the yield point if the system has a low initial slip modulus: the point of the intersection of the two slopes would be located further away from the load-deformation curve. (Muñoz *et al.* 2008) also observed that the method by Yasumura and

Kawai (1998) generally provides better estimates of the yield load and the calculated point is located on the actual load-deformation curve. The bilinear approaches (i.e. EN 12512 & SIA 265:2012 and Yasumura and Kawai 1998) help balancing the yield loads depending on the curve shape, despite the problems observed for methods in EN 12512 & SIA 265 when applying it to connections with low slip moduli. The EEEP method often results in unrealistic points in the cases considered by Muñoz *et al.* (2008). Since it does not consider the shape of the graph and as a consequence both a brittle and a ductile behaviour may gain the same value of ductility, Jorissen and Fragiacomio (2011) suggest a modification of the EEEP method in Equation (17), dividing the total energy (area underlying the curve) by the energy up to the point of yielding as shown in Equation (18). This method can therefore also be placed into the group of relative definitions.

F. Brühl (2020) evaluated the impact of ductility for the design of structures and stated that the yielding point should be defined only for connections with a certain ductile behaviour, hence, no yield point should be given for brittle behaviours. In his analysis he focuses on the methods in EN 12512 & SIA 265; the 5% diameter offset method and the EEEP method. Moreover, F. Brühl (2020) combines the method in EN 12512 & SIA 265 with the method by Yasumura and Kawai (1998), by projecting the yield point horizontally onto the actual load-deformation curve.

Given the considerations as described above in the previous studies, in this paper the following three methods for the determination of the yield point will be applied: EN 12512 & SIA 265, EEEP and Yasumura and Kawai (1998), as illustrated in Figure 3.

Classification and levels of ductility

Though asking for “connections of adequate ductility” when mentioning the possibility of internal load-redistribution, Eurocode 5 does not provide any information about different levels of ductility of connections what would be considered as adequate.

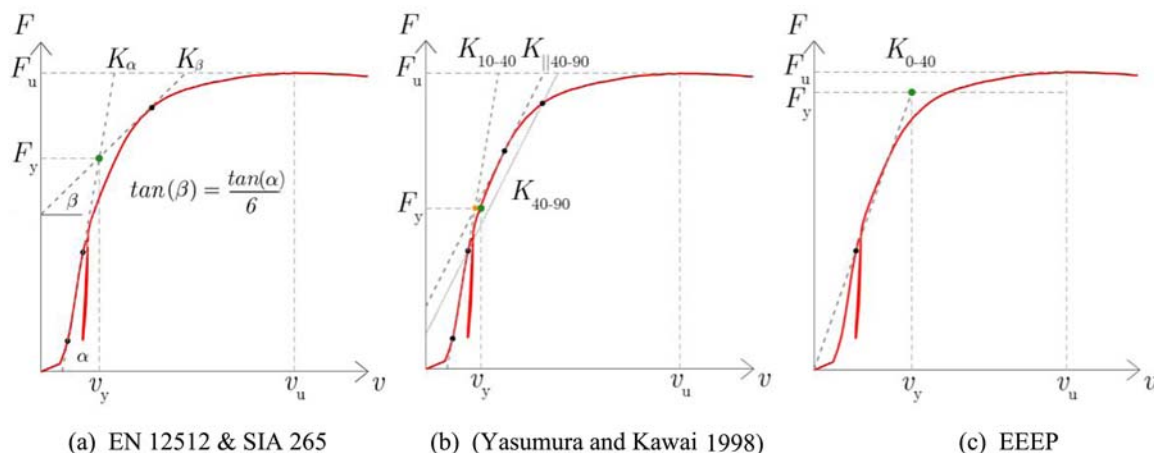


Figure 3. Some definitions of the yield point.

Table 1. Ductility levels specified in SIA (2012) according to Equation (10).

Configuration	Ductility D_f
Dowelled and bolted connections with a configuration satisfying less than 2 plastic hinges in the faster per shear plane	$D_f = 1 - 2$
Dowelled and bolted connections with a configuration satisfying 2 plastic hinges in the faster per shear plane	$D_f > 3$

The Swiss Standard SIA 265 distinguishes two different levels of ductility for different types of connection as summarized in Table 1. The definition of ductility is based on the deformation at failure according to Equation (10). The lower ductility levels with $D_f \approx 1$ correspond to connections that fail in a brittle way or with minimal plastic deformation when less than 2 plastic hinges per shear plane develop in the fastener.

The ductility levels proposed by Smith *et al.* (2006) and shown in Table 2 use the deformation at ultimate (maximum) load for the ductility ratio according to Equation (9). A broader distinction between different ductility levels is made compared to the Swiss Standard SIA 265, however, no indications on how to achieve these levels are made.

Material and methods

Test results from Jorissen (1998)

In this paper results from tests on bolted connections are evaluated that were carried out by Jorissen (1998) at TU Delft. These tests were performed to study the load-carrying capacity and failure mechanism in single and multiple fastener connections with dowel-type fasteners loaded parallel to the grain. Although the failure mechanism of a single fastener connection is ductile, a multiple fastener connection may change into a brittle failure mode (and consequently, the EYM is not applicable anymore). The result of this study is a reduction factor on the load-carrying capacity, the so-called $n_{ef} \leq n$ implemented in Eurocode 5, to avoid brittle failure modes (and consequently the EYM can still be applied for multiple fastener connections).

The connections were made as timber-timber connections with dowels loaded parallel to the grain in double shear. Bolts were used with steel qualities between 4.6 and 6.8 and yield strengths calculated from the bending moment of $f_y \approx 514 - 680 \text{ N/mm}^2$. No washers were applied and a gap between the bolt head and timber surface was kept to eliminate the rope effect; additionally two sheets of Teflon, to reduce friction were applied in the interfaces. The following parameters were varied in the test series with mostly 10–30 specimens (5–6 specimens as a minimum) (see also Figure 1): member thickness of the side (t_s) and middle (t_m) members, dowel diameter (d), number of fasteners in a row

Table 2. Ductility levels proposed by Smith *et al.* (2006) according to Equation (9).

Classification	Average ductility D_u
Brittle	$D_u \leq 2$
Low-ductility	$2 < D_u \leq 4$
Moderate ductility	$4 < D_u \leq 6$
High-ductility	$D_u > 6$

(n), number of rows of fasteners (m) (only 1 or 2 rows), spacing of the fasteners a_1 , end distance a_3 . The density (ρ) of the timber members was recorded and has a mean value of 450 kg/m^3 with a coefficient of variation of 9,8% and a corresponding characteristic value $\rho_k = 378 \text{ kg/m}^3$.

The test setup followed EN 1380 (CEN 2009) with most of the specimens being tested in compression and a small number in tension. An illustration of the test setups is shown in Figure 4. The deformation between the connected members was measured between the side members and middle member on both sides of the specimen in the centre of the connection by means of LVDT.

Methods

General

The following parameters were recorded in the tests: time, load, machine deformation, deformation of LVDT on both sides of the connection. For the further evaluation of slip modulus and load-deformation behaviour in this paper the mean deformation measured by the two LVDT on both sides for the connection was used. A reloading cycle was performed according to EN 26891 (CEN 1991).

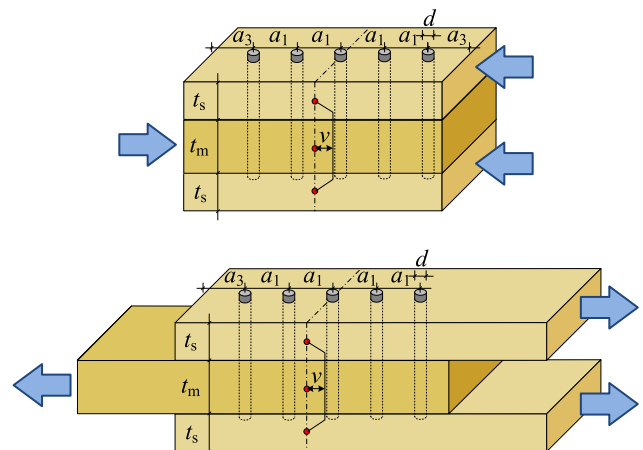
Slip modulus

The slip modulus in the serviceability limit state K_s (corresponding to K_{ser} in Eurocode 5 and SIA 265) as the secant slip modulus between 10% and 40% of the estimated maximum load and the elastic slip modulus K_e were calculated according to EN 26891 (CEN 1991). For the evaluation of the impact of individual parameters on the slip modulus of connections the test series were sampled into groups of equal configurations.

The following non-linear regression model was used for the evaluation of the impact of parameter X (e.g. diameter or row of fasteners) on the slip modulus K :

$$K(X) = a \cdot X^b \quad (19)$$

The slip modulus from Equation (19) is defined per fastener

**Figure 4.** Illustration of the test setups in compression and tension from Jorissen (1998) with denotations of connection geometry and measurement positions of deformations.

and per shear plane. The different test series in the database of Jorissen (1998) exhibited different numbers of specimens. Therefore, in a first step, the smallest number of specimens in the observed test series was determined and the regression was performed with an equal number of randomly selected data points for all test series. This procedure was repeated many times (1000) and the final regression parameters were taken as the mean of these repetitions. This ensures equal weighting of all test series.

Ductility

Similar to the slip modulus, the influence of different parameters on the different relative and absolute ductility definitions in Equations (9)–(16) is analysed and regression equations are derived. The yield point is calculated based on the EN 12512 & SIA 265, but comparison with the other methods illustrated in Figure 3 is made.

Results and discussion

Selected influences on slip moduli

Diameter d

Despite the large number of tests performed by Jorissen, the majority of the tests has been made with fastener diameters between $d \approx 11 - 12$ mm and only a small number of series with a wider difference of fastener diameters have been performed. These series (11, 14 and 35) have a configuration of the connection with relative thickness of the side members $t_s/d = 3.04 \sim 3.38$, number of fasteners in a row $n = 5$, number of rows of fasteners $m = 1$, spacing $a_1/d = 7$ and end-distance $a_3/d = 7$. The regression of slip modulus $K_s(d)$ in dependency of fastener diameter d derived from these tests is shown in Figure 5 together with a comparison of the values from SIA 265 and EC5. The following regression function can be derived:

$$K_s(d) = 0.029 \cdot d^{2.24} \text{ [kN/mm]}; \text{ per shear plane; } d \text{ [mm]}.$$

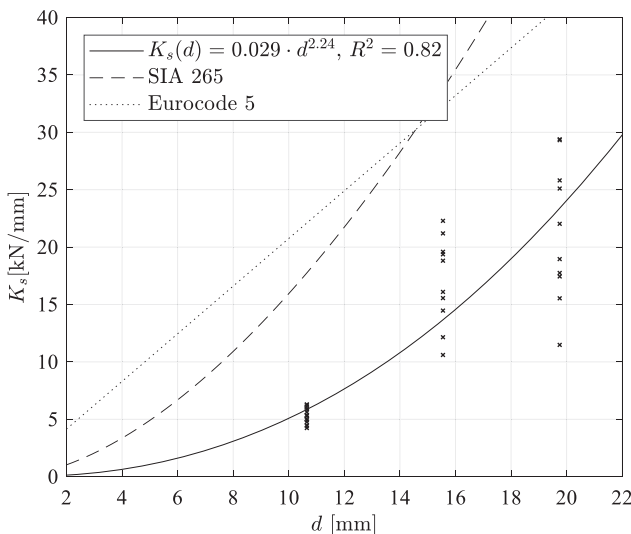


Figure 5. Impact of diameter d on slip-modulus K_s in a selected test series and comparison with slip moduli K_{ser} from standard SIA 265 and Eurocode 5.

Though the absolute slip modulus from the tests is considerably smaller than the values according to the standards, the impact of dowel diameter on the regression of slip modulus $K_s(d)$ is considerably higher compared to the specifications in Eurocode 5, SIA 265 or other codes. The coefficient of determination is $R^2 = 0.82$. A higher impact of dowel diameter compared to Eurocode 5 was also observed by Lemaître *et al.* (2018). A linear impact of the fastener diameter on the slip modulus as given in Eurocode 5 can be expected if the load-deformation behaviour is governed by embedment of the fastener. However, if the elastic or plastic deformation of the fastener dominates the load-deformation behaviour, an over proportional impact of the dowel diameter on the slip modulus can be expected.

Thickness of members

As can be derived from the EYM, the thickness of the timber members has a major impact on the load-carrying capacity of connections. The load-carrying capacity depends on the embedment strength of the timber and, when plastic hinges develop in the fasteners, the yield moment of the fasteners. In contrast, the slip modulus at serviceability limit state corresponds to small deformations within the elastic deformation state of the connection well below the yield point. Hence, it can be questioned, if the thickness of the timber members has a similar impact on the slip modulus as on the load-carrying capacity.

The required thickness at the transitions between the different failure modes according to the EYM is illustrated in Figure 6. The required thickness of the side members in order to assure a failure mode with two plastic hinges in the fasteners is $t_s/d \approx 4.95$, when assuming an embedment strength and yield moment according to Eurocode 5, with $\rho = 450 \text{ kg/m}^3$, $f_u = 600 \text{ N/mm}^2$ and $d = 11 \text{ mm}$. The thickness of the side members separating the failure mode with embedment and one plastic hinge is $t_s/d \approx 1.45$.

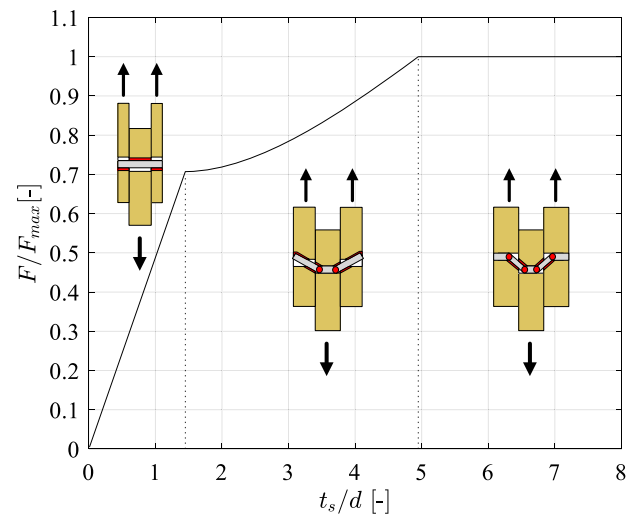


Figure 6. Relative resistance of a dowelled connection with a fastener in double shear in dependency of the relative side member thickness for $\rho = 450 \text{ kg/m}^3$, $f_u = 600 \text{ N/mm}^2$ and $d = 11 \text{ mm}$. The thickness of the central member is $t_m = 2 \cdot t_s$.

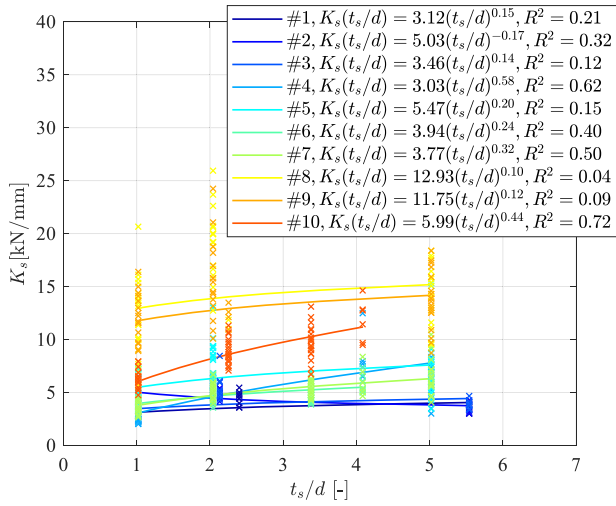


Figure 7. Impact of the slenderness ratio of the side member thickness t_s/d on slip-modulus K_s in selected test series.

The impact of the thickness of the side members on the slip modulus was evaluated from a selection of 10 series of the test results (see Figure 7). When determining the regression function of slip modulus $K_s(t_s/d)$ in dependency of solely the side member thickness, the exponent of the slenderness ratio of the side member thickness t_s/d is in the range between 0.1 and 0.58 with a mean value of 0.21 and one negative value of -0.17 . In addition, the coefficient of determination R^2 is in the majority lower than 0.4. Hence, the impact of the side member thickness on the slip-modulus can be considered to be low (with a slightly positive trend). The trend confirms the modelling results by Lemaître *et al.* (2018), where a general increase of stiffness with increasing slenderness were observed.

Variability of slip modulus

So far only the mean values of slip moduli are given in standards. However, in order to be able to perform sensitivity analyses of the force distribution in complex structures, also the variability of the connection slip modulus should be considered. The variability of the present large data set was evaluated by selecting those series with diameters $d \approx 11$ mm, numbers of fasteners in a row $n > 1$ and one row of fasteners $m = 1$. For these cases the following regression function for K_s per fastener and shear plane according to EN 26891 was determined in dependency of both n and t_s/d :

$$K_s\left(n, \frac{t_s}{d}\right) = 0.81 \cdot n^{1.196} \cdot \left(\frac{t_s}{d}\right)^{0.145} \quad (20)$$

[kN/mm] per fastener and shear plane

In this regression equation, considering both the number of fasteners in a row and the slenderness ratio of the side member thickness t_s/d , the latter has a slightly lower impact compared to the evaluation done in the previous sub-chapter when considering only t_s/d in the regression and deriving a mean value of the exponent of 0.21.

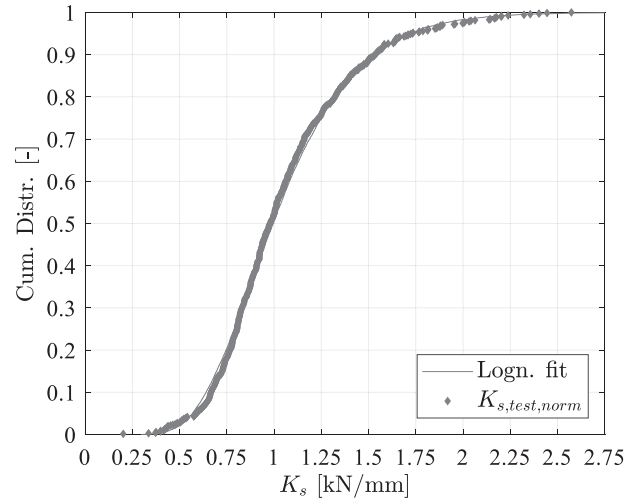


Figure 8. Cumulative distribution of slip modulus K_s for $n = 1$ and $t_s/d = 5$ ($d \approx 11$ mm).

The cumulative distribution shown in Figure 8 are the test results of the slip modulus normalized with regard to $n = 1$ and $t_s/d = 5$ by Equation (20) ($K_s = 0.81 \cdot 1 \cdot 5^{0.145} = 1.023$ kN/mm, per shear plane, corresponding to median value in Figure 8). The coefficient of variation of the slip modulus K_s is approx. 34.7%. The corresponding slip-moduli according to the standards SIA 265 and Eurocode 5 are: $K_{ser,SIA} = 3.26$ kN/mm and $K_{ser,EC5} = 4.57$ kN/mm, respectively. This considerable difference in the mean slip modulus derived from the tests and the calculated slip moduli according to standards was already mentioned by Jorissen (1998) and related to the larger number of fasteners and their individual hole clearance.

The regression function for the elastic slip modulus K_e can be determined to:

$$K_e\left(n, \frac{t_s}{d}\right) = 6.95 \cdot n^{1.13} \cdot \left(\frac{t_s}{d}\right)^{-0.19} \quad (21)$$

[kN/mm], per fastener and shear plane

The cumulative distribution of the test results of the elastic slip modulus normalized with regard to $n = 1$ and $t_s/d = 5$ by Equation (21) ($K_e = 6.95 \cdot 1 \cdot 5^{-0.19} = 5.12$ kN/mm) is shown in Figure 9. The tests data of the elastic slip modulus K_e has a coefficient of variation is approx. 32.1%.

Determination of K_u

Due to the strong non-linearity of the load-deformation behaviour of connections with different failure modes, there are considerable differences between K_s and K_u . In Figure 10 different examples of load-deformation curves of connections with dowel-type fasteners are given. Depending on the relative thickness of the side members the different failure modes according to the EYM are reached. A decrease in the relative spacing a_1/d (or end distance a_3/d) leads not only to a decrease of maximum load but also to a reduction of the deformation capacity and, consequently, the ductility. Only with sufficient spacing and end-distances considerable

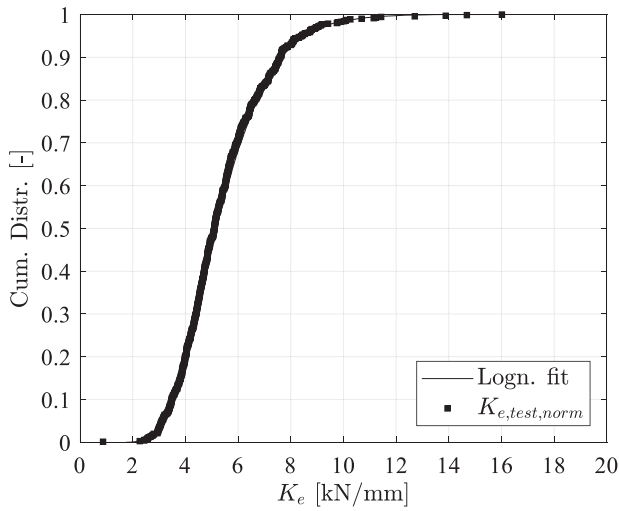


Figure 9. Cumulative distribution of elastic slip modulus K_e for $n = 1$ and $t_s/d = 5$ ($d \approx 11$ mm).

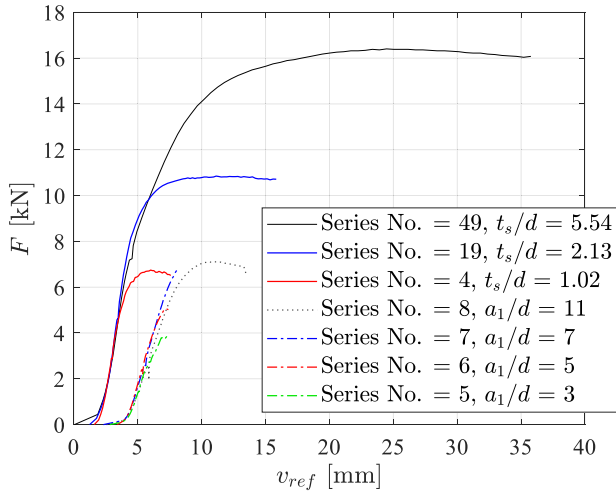


Figure 10. Representative load-deformation curves for different test series with $n = 3$, $a_1/d = 11$ and $a_3/d = 7$ for series numbers 4, 19 and 49 and $n = 5$, $t_s/d = 1.02$ and $a_3/d = 7$ for series 5–8.

plastic deformations can be achieved. It has to be evaluated how this change in deformation capacity effects the slip modulus at ultimate load K_u .

The evolution of secant slip modulus K_{sec} in relation to K_s is shown in Figure 11. Within the linear range of the load-deformation curve up to approximately 50%–70% of the maximum load F_u the ratio K_{sec}/K_s is approximately 1. Values larger than 1 can occur due to the convex shape of the load-deformation curve. If sufficient deformation capacity is available, the ratio drops down to values of up to $K_{sec}/K_s \approx 0.2$, when reaching the plastic part of the curve with increasing load. The threshold of $K_u = \frac{2}{3}K_{ser}$ according to Eurocode 5 is reached at loads F exceeding 80%–100% of F_u . The test series with reduced spacing $a_1/d \leq 7$ show ratios $K_{sec}/K_s \approx 1$ up to failure. That means that failure is reached within the linear elastic deformation state of the connection which is related to a brittle failure mode of the connection due to e.g. splitting

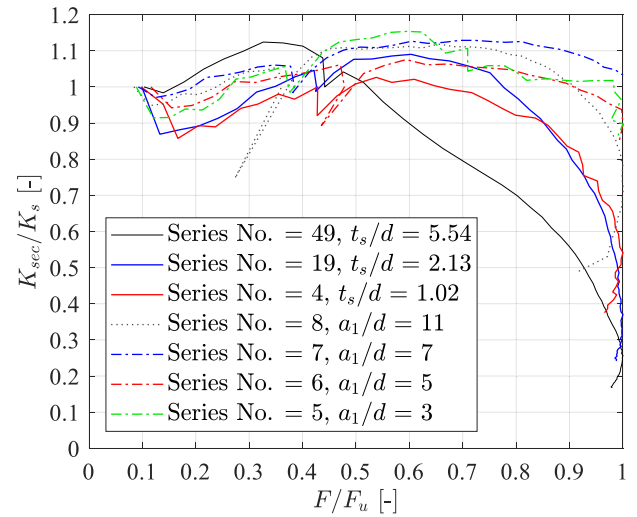


Figure 11. Relation of secant slip-modulus K_{sec} to slip-modulus K_s along different load levels of the representative load-deformation curves.

of the timber members. In these cases, it might be unconservative and even unsafe to assume a slip modulus in the ULS of $K_u = \frac{2}{3}K_{ser}$, especially in statically indeterminate structures, when stiffer elements or connections might attract higher loads compared to softer ones.

In Figure 12 the relation of secant slip-moduli at maximum load K_u to slip-modulus K_s in dependency of relative spacing a_1/d and side member thickness t_s/d are shown. It can be seen that (except for connections with single fasteners, for which $a_1/d = 0$), certain minimum values of both relative spacing and member thickness need to be fulfilled in order to reach a softer connection behaviour with values of $K_u < \frac{2}{3}K_s$. These configurations are related to a ductile connection behaviour, which requires larger spacing and member thickness for higher number of fasteners in a row. In the following section, the different influences on the ductility and the resulting levels of ductility will be evaluated.

Influences on ductility

From the test results, the values of ductility according to the different definitions in Equations (9)–(16) have been calculated in order to determine and evaluate the parameters with influence on these values. The following generic regression function for the ductility in dependency of the number of fasteners in a row n , side member thickness t_s/d and the relative spacing a_1/d is defined:

$$D = \alpha \cdot n^\beta \cdot \left(\frac{t_s}{d}\right)^\gamma \cdot \left(\frac{a_1}{d}\right)^\delta \quad (22)$$

It should be considered that Equation (22) is unitless [-] for definitions of ductility in Equations (9)–(13) whereas it is defined in [mm] for the definitions in Equations (14)–(16). Equation (22) can be extrapolated to connections with single fasteners with $n = 1$ by using the end grain distance a_3/d instead of the spacing.

In Table 3 the regression parameters for Equation (22) and the different definitions of ductility in Equations (9)–(16) are

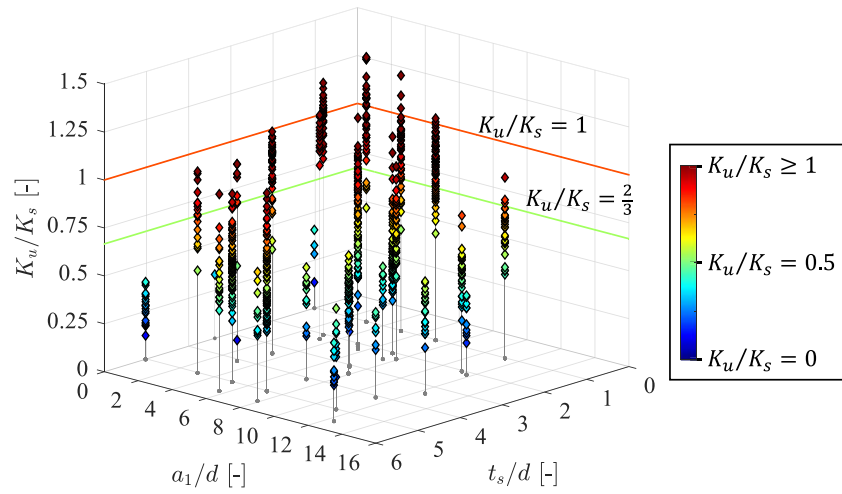


Figure 12. Relation of secant slip-modulus K_u at ultimate (maximum) load to slip-modulus K_s of individual tests results in dependency of relative spacing a_1/d and side member thickness t_s/d .

Table 3. Regression parameters for equation (22) of ductility definitions in equations (9)–(16).

	α	β	γ	δ
D_u	1.81	−0.300	0.234	0.405
D_f	2.05	−0.396	0.242	0.471
D_{uy}	0.969	−0.644	0.706	1.03
D_{fy}	1.22	−0.791	0.708	1.11
C_u	0.398	−0.228	0.182	0.315
C_f	0.455	−0.289	0.176	0.315
$D_{f/u}$	1.12	−0.0918	0.00648	0.0677
D_{fu}	0.221	−0.946	0.497	1.29

summarized for the definition of the yield point according to the method in EN 12512 & SIA 265. The relative spacing of the fasteners and the relative thickness of the side members have the largest positive impact on all the definitions of ductility shown, whereas the ductility level decreases with an increasing number of fasteners in a row n .

Comparing similar relative and absolute definitions shows that those definitions based on the deformation at failure

(when the load drops below 80% of F_u) (e.g. D_f or D_{fy}) give larger ductility values compared to the definitions based on the deformation at ultimate (maximum) load F_u (e.g. D_u or D_{uy}).

The relative ductility definitions C_u and C_f based on deformation at ultimate or failure load, respectively, show a lower impact of studied parameters (n , t_s/d and a_1/d).

The two ductility definitions comparing the deformations at ultimate and failure load as a relative ($D_{f/u}$) or absolute (D_{fu}) criterion are independent of the determination of yield point and describe the post-peak behaviour of the connection. The relative ductility definition ($D_{f/u}$) shows the least impact of the studied parameters and can be seen as not being a suitable criterion to distinguish different ductility levels.

The dependency of the relative deformation based ductility definition D_f in Equation (10) on both the side member thickness t_s/d and the relative spacing a_1/d is shown in Figure 13 for all test results. This ductility definition is used

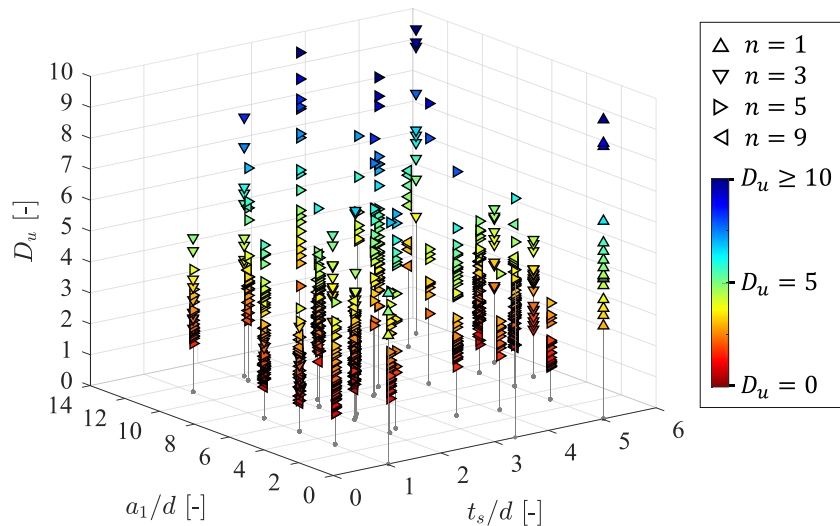


Figure 13. Ductility D_f (Equation (10)) of tests with different number of fasteners in a row n in dependency of the relative spacing a_1/d and side member thickness t_s/d .

in SIA 265 and the ductility levels in Table 1 are specified. A wide scatter of the ductility values determined in the tests can be seen in Figure 13, and a trend of lower values for thinner side member thickness t_s/d and smaller relative spacing a_1/d can be observed. It can be seen that even for $t_s/d \geq 5$, which corresponds to a failure mode with two plastic hinges in the fastener per shear plane considering sufficient spacing and end-distance, the ductility may be smaller than $D_u < 3$ as specified in SIA 265 and even $D_u < 2$ (red and orange colour). These small values can be related to small relative spacing or series with a large number of fasteners in a row.

The impact of the number of fasteners in a row n , relative spacing a_1/d , and relative side member thickness t_s/d on the ductility D_f is shown in Figure 14–16, respectively. The most prominent influences can be observed from Figures 14 and 15: The ductility decreases with an increasing number of

fasteners in a row and increases with increasing spacing between the fasteners. The impact of the side members thickness is not as clearly distinguish as can be seen in Figure 16. Even for large side members thickness low levels of ductility D_f occur for a larger number of fasteners in a row and small spacing.

A further analysis of the impact of side member thickness t_s/d on load-deformation behaviour can be made by analysing the absolute ductility D_{fy} according to Equation (15) as shown in Figure 17. The single test series consists of mostly 10–21 individual specimens with few series of only 5–7 specimens. The different ductility levels can be clearly distinguished and the need to avoid small side members thickness $t_s/d \approx 1$ with failure modes without yielding of the fasteners becomes obvious when aiming at ductility. By assuring a spacing of $a_1/d > 7$ for those connections a

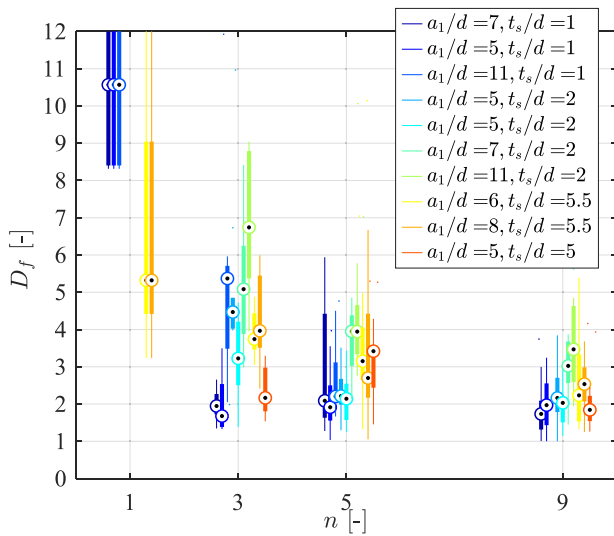


Figure 14. Impact of number of rows of fasteners n on ductility D_f (Equation (10)) of selected test series.

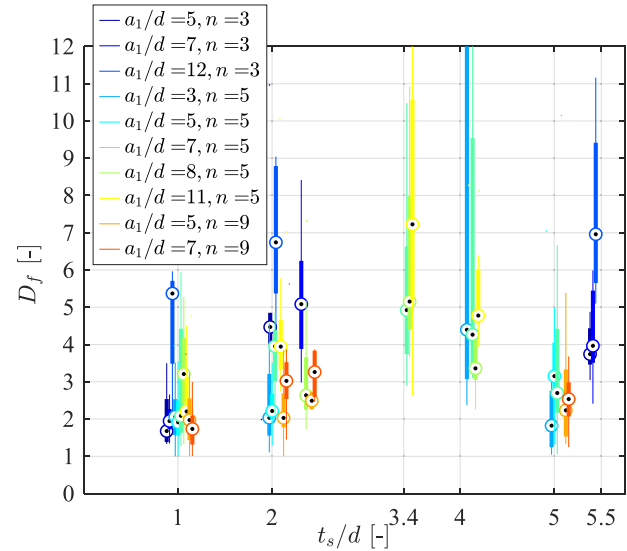


Figure 16. Impact of side member thickness t_s/d on ductility D_f (Equation (10)) of selected test series.

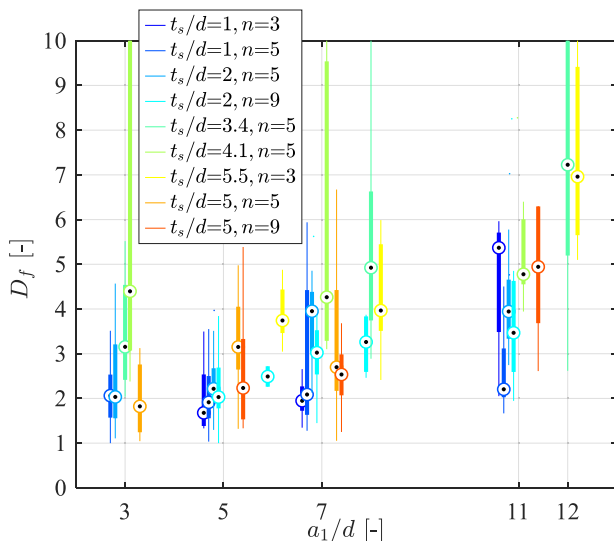


Figure 15. Impact of relative spacing a_1/d on ductility D_f (Equation (10)) of selected test series.

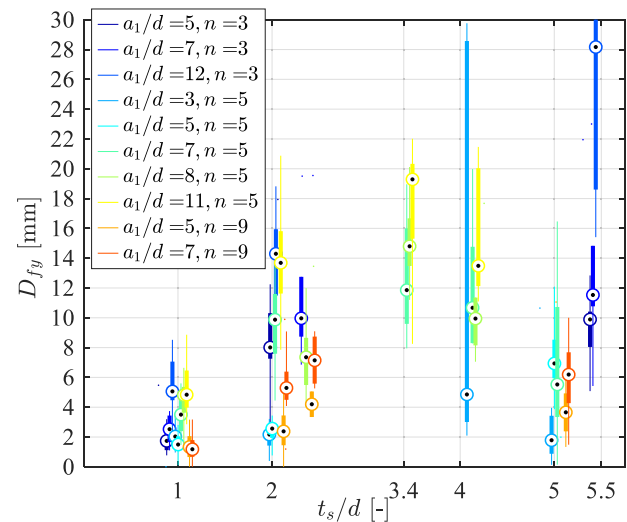


Figure 17. Impact of side member thickness t_s/d on ductility D_{fy} (Equation (15)) of selected test series.

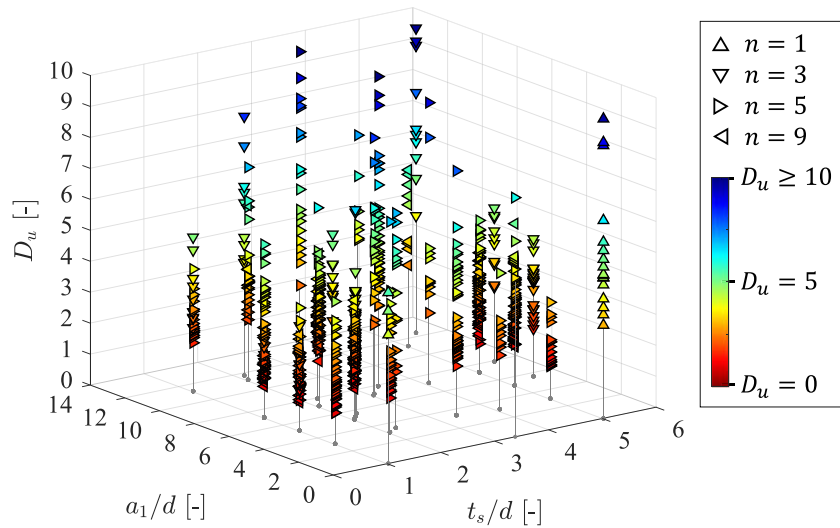


Figure 18. Ductility D_u (equation (9)) of tests with different number of fasteners in a row n in dependency of the relative spacing a_1/d and side member thickness t_s/d .

deformation larger than the fastener diameter ($d \approx 11$ mm) can be achieved. Due to the larger absolute ductility and deformation at failure, the scatter in the results increases with increasing slenderness.

The ductility definition D_u in Equation (9) is shown in Figure 18. This definition was discussed by Smith *et al.* (2006) and ductility levels are proposed in Table 2. It can be seen that even for large side member thickness $t_s/d \geq 5$, which corresponds to a failure mode with two plastic hinges in the fastener per shear plane, the ductility may be smaller than $D_u < 3$ and even $D_u < 2$ (red and orange colour). These small values can be related to small relative spacing or series with a large number of fasteners in a row.

The regression parameters for the ductility in Equations (10) and (15) determined according to the different methods for determination of yield point are summarized in Table 4. In comparison with the values given in Table 3, the different influence of parameters can be observed. The method by EEP leads to a higher impact of the number of fasteners in a row on the ductility D_f but to a lower impact of side member thickness and spacing. In contrast, for the absolute ductility D_{fy} based on the yield point by the method of Yasumura and Kawai (1998) the impact of side member thickness and spacing is higher compared to the other methods.

It can be summarized that the ductility increases with increasing spacing and member thickness; the ductility

decreases with an increasing number of fasteners. This behaviour is influenced by the different failure modes that may occur in the connection in dependency of its configuration. Failure modes with two plastic hinges in fastener per shear plane should be aimed at, which can be achieved by ensuring sufficient timber member thickness together with sufficient spacing between the fasteners. The required spacing in return is dependent on the number of fasteners in a row: a larger number of fasteners in a row require larger spacing in order to prevent early brittle failure due to splitting. If all these requirements are met, large relative and absolute ductility can be achieved. Particularly the absolute ductility definitions can be considered as a good criterion to assure sufficient deformation capacity of the connection in order to provide the possibility for load-redistribution within a connection with multiple fasteners and potentially also between different connections.

Conclusions

In this paper, the background and specifications of slip modulus and ductility in different standards and literature are reviewed and a large number of test results on bolted timber connections is evaluated regarding the load-deformation behaviour.

The review of the background and specifications of the slip modulus shows that the formulas given in Eurocode 5 and SIA 265 are based on only few test series that may not be suitable to represent modern connections used in contemporary timber structures. The formulas in Eurocode 5 and SIA 265 are based on fastener diameter and timber density and consider only a part of the parameters influencing the load-carrying capacity of connections with dowel type fasteners. The background of certain assumptions that were implemented in design codes is vague, such as the impact of the load-to-grain angle on the slip modulus or the load and deformation levels defining the slip

Table 4. Regression parameters for equation (22) of the ductility definitions in equations (10) and (15) based on the method for determination of yield point by Yasumura and Kawai (1998) and by EEP.

	α	β (Yasumura and Kawai 1998)	γ	δ
D_f	0.848	−0.18	0.241	0.467
D_{fy}	0.322	−0.762	1.1	1.79
		EEP		
D_f	3.45	−0.452	0.164	0.242
D_{fy}	1.63	−0.759	0.621	0.982

modulus at ultimate limit state. In addition, it is not mentioned in either Eurocode 5 and SIA 265 or other available literature how to consider the variability of stiffness in the ultimate limit state.

The load-deformation behaviour of timber connections with dowel-type fasteners can exhibit considerable ductility due to which brittle failure modes are prevented. Different relative or absolute definitions of ductility based on deformations or energy formulations can be found in literature. However, only few specifications on how to consider ductility can be found in the design codes.

In this paper, the test results by Jorissen (1998) from TU Delft on bolted connections were evaluated with regard to the influences of the connection configuration on the slip modulus and ductility. The slip modulus in the serviceability limit state shows the highest dependency on the fastener diameter and number of fasteners in a row, whereas the side member thickness and fastener spacing show only a minor impact. Since all the test specimens were made from softwood with only a small variability in density, it was not possible to quantify the impact of density in detail.

The level of ductility achieved in the tests depends on the different definition absolute or relative definition of ductility and the method for the determination of the yield point. The spacing between fasteners and the thickness of the side members have a positive impact on the ductility of the connection: the larger the spacing and thickness the higher the ductility. Furthermore, the ductility decreases with an increasing number of fasteners in a row. It is recommended to apply an absolute definition of ductility in order to consider the possibility for load redistribution between fasteners in a connection and between different connections also for the case that tolerances and clearances in the connection exist.

Based on the study presented in this paper a need for further research can be defined related to dowel-type fasteners: different connection configurations should be evaluated with regard to the slip modulus and ductility, particularly connections with a broader range of soft- and hardwoods, different timber-timber and steel-timber connections, different types of fasteners, different numbers of fasteners in a row and rows of fasteners.

The impact of the entire non-linear load-deformation on the load-carrying behaviour of more complex structures in the ultimate limit state should be evaluated more in detail in order to give better guidance on how to account for the possibility of load-redistribution between fasteners and between connections in such structures.

Also, the variability of the slip-modulus and ductility should be accounted for and consistent approaches for the definition of yield point should be defined.

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